James Clerk Maxwell

The pace of electrical development makes it difficult to realize that only a century has elapsed since publication of the laws of electromagnetic action by the genial Scotsman. Maxwell is linked with Newton and Darwin – a Cambridge triumvirate who fundamentally changed the world's concepts of physical reality

Bern Dibner *Burndy Corporation*

James Clerk Maxwell was born on June 13, 1831, in Edinburgh into an upper-middle-class home; his father was a practicing attorney and a descendant of the Lords Maxwell. (The year 1831 was also the year in which Faraday discovered and announced electromagnetic induction.) Maxwell spent his youth and was educated by private tutors at an estate in Scotland called Glenlair, a modest mansion house of grey stone located in wooded country about seven miles from Castle Douglas. From the age of 10 until he was 16 he attended the Edinburgh Academy. His scientific interests were awakened early; while still at the Academy, when he was only 15 years old, he prepared a paper on advanced geometry that was accepted and read by Professor Forbes before the Royal Society of Edinburgh. Later Maxwell matriculated at Edinburgh University, where he specialized in mathematics, physics, and chemistry. He remained at Edinburgh from 1847 until October 1850, when he transferred to Peterhouse College, Cambridge, but switched to the university's Trinity College so that he might obtain a Fellowship in mathematics. From his position as Fellow of Trinity, he advanced to the post of professor of natural philosophy at Marischal College and the University of Aberdeen. At Trinity, Maxwell won the honors of Second Wrangler and became Second Smith's Prize Man in 1854.

Although he was a man of rather formidable scholarship, Maxwell was also known as a man of humor. As he became more deeply involved in the problems of physics, he would build models to illustrate some difficult or abstract relationship; one such device he called his "dynamic top." The story is told that he had the top with him at Cambridge and displayed it one evening while entertaining a party of old friends in his room. When the party departed, the top was left spinning on the table. On arising the following morning, Maxwell saw one of his guests of the previous evening approaching across the quadrangle; he jumped out of bed, set the top spinning again, and quickly slipped under the blankets. The visitor was quite surprised to find the top still spinning on the table.

In the summer of 1860, at the age of 29, Maxwell was selected from a group of five professors for the chair of natural philosophy at King's College, London. The five years during which he held this post were probably his most productive, because his two most important papers ("Physical Lines of Force" and "A Dynamical Theory of the Electromagnetic Field") date from this period.

In addition to formulating the equations of the electromagnetic field and predicting the electromagnetic theory of light, he also participated in the determination of the absolute unit of electrical resistance. His work in optics during this time included accurate determinations of colors and the response to various colors by a normal and a color-blind eye. He worked on the changes in the viscosity of gases with variations of temperature and pressure and concerned himself with the dynamic theory of gases while at King's. His notebooks, now at the college library, show that while there he was already pre-

James Clerk Maxwell, 1831–1879. Among his many contributions to physics was the mathematical determination of the electromagnetic field just a century ago. This explained the nature of light and led through Hertz to the discovery of the extensive electromagnetic spectrum.

paring outlines of his classic *Treatise on Electricity and Magnetism*, a work he completed between 1865 and 1870, after he had retired to his home in Glenlair. The treatise was published in 1873, two years following his appointment as professor of experimental physics at Cambridge.

When Maxwell was graduated from Cambridge, in 1854, he took with him two important prizes; to these he added the coveted Adams Prize in 1857 with a paper "On the Stability of the Motion of Saturn's Rings." Saturn's rings had been the subject of great conjecture since their discovery by Galileo in 1610. In 1655 Huygens correctly identified them as rings, and announced this fact in 1659. Maxwell, in his essay, showed that the rings could not be solid or of continuous structure, but that they must consist of innumerable small fragments spinning around the great planet like myriads of satellites. These conclusions on the particle nature of the rings were confirmed 38 years later by the American astronomer James Keeler, whose spectroscope showed what Maxwell had deduced: the outermost meteorites of the rings rotate at a slower velocity than the inner ones. With this essay at which Maxwell had labored for two years, his reputation as an important mathematical physicist was permanently established.

Maxwell's serious interest in the study of electricity began in 1854 when the subject was still in an anomalous condition. His first publication in the field was read to the Cambridge Philosophical Society late in 1855 when

he was 24 years old; it bore the title, "Faraday's Lines of Force." In his introduction to his later *Treatise on Electricity and Magnetism*, Maxwell wrote:

> "*Before I began the study of electricity I resolved to read no mathematics on the subject till I had first read through Faraday's* Experimental Researches on Electricity. *I was aware that there was supposed to be a difference between Faraday's way of conceiving phenomena and that of the mathematicians, so that neither he nor they were satisfied with each other's language. . . . As I proceeded with the study of Faraday, I perceived that his method of conceiving the phenomena was also a mathematical one, though not exhibited in the conventional form of mathematical symbols. I also found that these methods were capable of being expressed in the ordinary mathematical forms, and thus compared with those of the professed mathematicians.*"[1]

He thus clarified the vague theory that Faraday had noted in 1832, in which he compared the diffusion of magnetic forces from a magnetic pole to ripples on water, to sound, or to the vibrations of light.

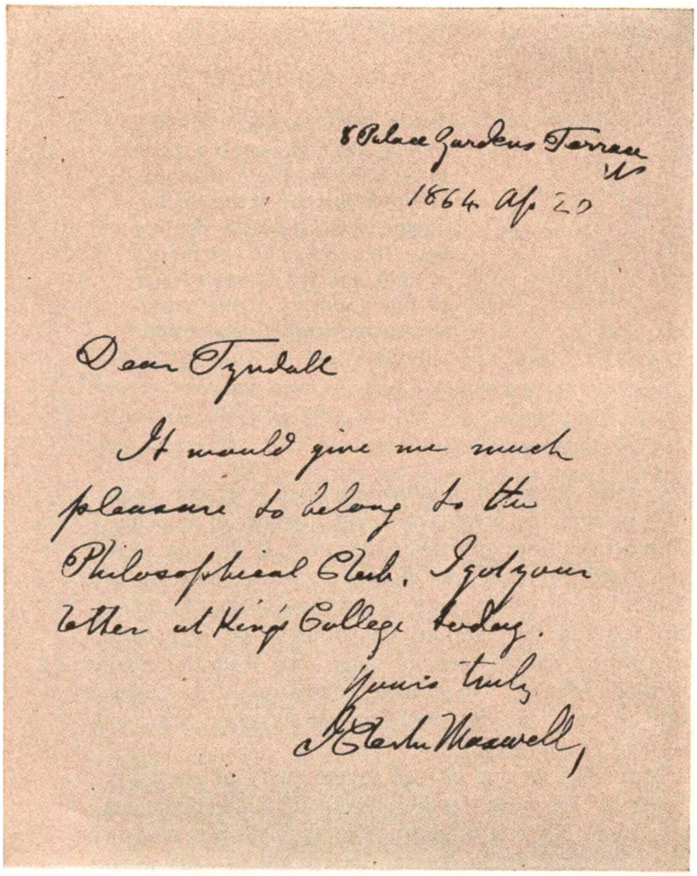
Inquiry into the nature of space as a transmission medium

Among the major problems that perplexed Maxwell was the effort to understand the transmission of force through space in which no matter exists. This had been a subject for study from Aristotle down through the ages. Newton proposed the law of universal attraction in 1687 and the electrical investigators of the 1700s added magnetism and electrostatics as fields of action at a distance. Laplace and Boscovich brought mathematical order on a cosmic scale, while Avogadro and Davy were involved with molecular affinities and action.

The influence of Faraday on Maxwell was continuous and profound. Faraday had concerned himself with intermolecular strain that led to a remarkable sequence of discoveries in electrolysis, electrostatic induction, specific inductive capacity, diamagnetism, and the effect of a strong magnetic field upon light. Unlike Maxwell, whose approach in treating the difficult subject was purely mathematical, Faraday, after 30 years of intensive experimentation, had concluded that electric and magnetic phenomena could best be understood and analyzed from the physical properties of the lines of force of the medium put into a state of tension by electric or magnetic stress. Maxwell readily followed the reasoning of Faraday and he could, with his mathematical training and predilection, expand the *Experimental Researches* of Faraday, in which not a single algebraic expression is shown (neither is there one in Newton's *Principia*).

Maxwell first met Faraday in 1860, shortly after he assumed his place as professor at King's College. His contact with Faraday at the Royal Institution, where Maxwell lectured in 1861, made him an admirer not only of Faraday the man, but also of Faraday the experimenter. Maxwell was engaged, in particular, by Faraday's concept of the nature of the space or field existing around a magnetized or electrified body. He thereupon decided to study this field and to give its properties mathematical expression. He realized then, as we do increasingly today, that there was more knowledge concerning the laws relating to matter, motion, and energy than there was an understanding of that which seemed to pervade everything and yet was resolved to nothing—space. He realized that "the work of mathematicians is of two kinds, one is counting, the other is thinking," and he regarded thinking as a nobler though more expensive occupation than counting. He wished to represent the physical universe not in directionless symbols, denoting mere quantities, but in dynamic vector terms in which one could think about a material system by describing the relative position of its parts. The mind had to shift from a three-coordinate system to a space in which each point has magnitude and direction.

In applying his analytic mind and mathematical command to electromagnetic problems, Maxwell did not follow the French school (Coulomb, Laplace, Poisson, and Ampère), which regarded electrical and magnetic phenomena as instances of *action at a distance*. Faraday's experiments in giving reality and form to magnetic and electrostatic *fields* with their lines of force emanating from a magnetic pole or a charged electric point prompted Maxwell to examine the physical properties of the surrounding space. Faraday had studied the curvature of the lines of force in an electrostatic field and had observed the apparent tendency of adjacent lines to repel one another as if each tube were impelled to distend itself laterally. This further implied that, transverse to the plane of distention, a contractile or attracting force must bal-



8 Palace Gardens Terrace
W
1864 Ap 20

Dear Tyndall

It would give me much pleasure to belong to the Philosophical Club. I got your letter at King's College today.

Yours truly
J Clerk Maxwell

A letter from Maxwell to John Tyndall, his biographer. Tyndall followed Faraday as director of the Royal Institution. (This letter is in the possession of the Burndy Library.)

ance it at right angles, that is, in the axis of motion of the lines of force.

From an examination of the sprinkling of iron filings on a magnetic field, Maxwell theorized that lines of tension emanated from the poles and that pressures were exerted at right angles to the lines of force. These might have arisen from a centrifugal force of eddies or vortices having axes parallel to the lines of force. However, such a reduction to a mechanical model implied that adjacent vortices revolved in opposite directions and therefore required an "idler wheel" to make similar motion possible. He then translated this scheme into magnetic and electric-current terms, and in a later paper used this means also to explain electrostatic phenomena.

Coherent theory developed

Toward the end of 1854, in analyzing each element involved in the transmission of a force from point to point in space, Maxwell finally succeeded in developing a coherent theory for the transmission of force by eliminating all elements except space itself. The existence of a ponderable medium of contiguous particles of matter was no longer required and space became the transmitting medium. Faraday's lines of force began to give way to strains in space. Maxwell clearly saw in this the orderly elements that he could express with mathematical precision to describe the theory of the field; this led finally to the generalization by Albert Einstein.

Maxwell developed his own mathematical symbolism to illustrate physical constants and variables, and supplemented these by models to clarify further a complex relationship. He never considered these models final and ultimate, but changed or discarded them when improvements came to mind. Studies of a model he designed to illustrate Faraday's important discovery that electric forces were produced from changes in magnetic forces, suggested to Maxwell that changes in electric forces would produce a magnetic force. He thus arrived at his greatest contribution to physics; and "Faraday's law" was therewith supplemented by "Maxwell's law" in the literature of electrical science.

In mathematically analyzing Faraday's studies on lines of force, Maxwell made no attempt to introduce any of his own observations or theories, but simply attempted to express Faraday's published work in crisp mathematical terms. This resulted in the important paper, "On Faraday's Lines of Force," which was presented in two parts (December 1855 and February 1856) before the Cambridge Philosophical Society and published by them in 1856. Maxwell sent a copy to Faraday at the Royal Institution in London and Faraday responded with surprise and pleasure at seeing his work expressed in such abstruse form. Yet Maxwell had stated in the paper:

"*Thus all the mathematical sciences are founded on relations between physical laws and laws of numbers, so that the aim of exact science is to reduce the problems of nature to the determination of quantities by operations with numbers. Passing from the most universal of all analogies to a very partial one, we find the same resemblance in mathematical form between two different phenomena giving rise to a physical theory of light.*"[2]

Maxwell expressed the relationship in equations, not as derived from mathematical summarization, but by beginning with Faraday's experimental results and considering the surrounding ether in mechanical terms. However, he later abandoned these, but retained the equations, and considered the lines of force as Faraday did—simply as pictures of action of a medium that filled space. Maxwell therefore repeated that he was simply arranging Faraday's ideas in mathematical form.

Two historic papers

As pointed out previously, it was while Maxwell was professor of natural philosophy at King's College (1860–1865) that he made two of his most important contributions to the physical sciences. The first of these, in 1862, was the paper "Physical Lines of Force," wherein Faraday's law of electromagnetic induction again prompted the creation of a model to illustrate the interaction of the two forces. The model clearly suggested that *changes* in the electric force produced a magnetic force with corresponding changes in electric and magnetic fields, causing the further propagation of waves in space. This paper contained equations linking electric and magnetic forces with such brilliance that when J. J. Thomson first read them as a boy of 18 his enthusiasm reached a point of ecstasy; he was impelled to copy the rather long paper in longhand, including some passages that he always considered obscure.

The second paper, published 100 years ago, in 1864, was "A Dynamical Theory of the Electromagnetic Field," his most profound synthesis. In this epochal 54-page paper, read on December 8, 1864, and printed in 1865 in the *Transactions of the Royal Society*,[3] Maxwell stated: "In these theories the force acting between the two bodies is treated with reference only to the condition of the bodies and their relative position, and without any express consideration of the surrounding medium." Maxwell asserted that unlike Faraday's actual physical lines of force with their properties of tension, repulsion, attraction, and motion, he (Maxwell) imagined these actions in hydrodynamic terms, which were much more readily reduced to mathematical form and provided an analog to the known electrical phenomena.

In considering electrostatic charges on insulating material, Maxwell referred to the work of Wilhelm Weber and Friedrich Kohlrausch, who had established the relationship between electrostatic and electrodynamic forces in standard units. An electrostatic unit of charge was defined as the repulsion at unit distance between two similar unit charges. Similarly, the unit of electrodynamic force was the repulsion between two electric currents traveling in wires of equal length, and moving past a given point in unit time. A proportionality was therefore established between electrostatic repulsion and the moving charges because of the difference in units. It is in this proportionality, resulting in length divided by time, that Weber and Kohlrausch obtained an expression with the same dimensions as a velocity. This they had shown to be of the order of 3×10^{10} cm/s, which Maxwell recognized to be close to the velocity of light. Using an ingenious torsion balance, Maxwell compared the repulsion between two static charges and the two current-carrying wires, and calculated the velocity of displacement currents in a dielectric. The results showed that these displacement currents in a dielectric, the current flow in a wire, and the velocity of light traveling in space were all similar—and agreed with the working mechanical model that he had conceived.

In his paper, Maxwell wrote:

"*The theory I propose may therefore be called a theory of the* Electromagnetic Field *because it has to do with the space in the neighbourhood of the electric or magnetic bodies, and it may be called a* Dynamical *Theory, because it assumes that in that space there is matter in motion, by which the observed electromagnetic phenomena are produced. . . . The general equations are next applied to the case of a magnetic disturbance propagated through a non-conducting field, and it is shown that the only disturbances which can be so propagated are those which are transverse to the direction of propagation and that the velocity of propagation is the velocity* v, *found from experiments such as those of Weber, which express the number of electrostatic units of electricity which are contained in one electromagnetic unit. This velocity is so nearly that of light, that it seems we have strong reason to conclude that light itself (including radiant heat, and other radiations if any) is an electromagnetic disturbance in the form of waves propagated through the electromagnetic field according to electromagnetic laws.*"[4]

Maxwell proposed his hypothesis in dynamical terms in which he referred to the *energy* of an electric current, *elasticity* of the medium, and *momentum* of a varying electromagnetic field. Recognizing a form of inertia in the phenomenon of self-induction and the manifestation of heat and work in an electric circuit, he saw fit to apply the mathematical expression of physics to electrokinetics. These relationships he expressed in 20 equations involving 20 variables. The importance of this paper was immediately recognized, but was the subject of much controversy because its disturbing conclusions indicated abandoning the old and faithful elastic solid ether.

Later, the mechanical models gave way to the subtleties of an all-pervading ether in which earlier mechanical notions attained purely geometric properties. Maxwell then formulated four relationships in two sets of symmetrical equations relating electric currents, dielectric displacement forces, and the intensity of a magnetic field. He further deduced from mechanical analogy and his mathematical equations that an electric field varying with time produced a magnetic force in every kind of medium, including insulators, or in empty space. This electric force varying with time produced displacement waves in a dielectric with the velocity of light. Magnetic forces were similarly produced; the wave fronts of the electric vibrations were at right angles to the direction of propagation, the magnetic force being generated at right angles to the electric surge. This constituted an electromagnetic wave. It was later stated that a light wave consisted of a series of alternating currents flowing in a dielectric (such as air) at extremely high frequency.

Maxwell first mentioned his great discovery in a letter to Michael Faraday on October 19, 1861, in which he stated, "From the determination by Kohlrausch and Weber of the numerical relation between the static and magnetic effects of electricity, I have determined the *elasticity* of the medium in air, and assuming that it is the same with the luminiferous ether, I have determined the velocity of propagation of transverse vibrations. The result is 193,088 miles per second. Fizeau has determined the velocity of light as 193,118 miles per second by direct experiment."[5] It must be noted that even though the two numbers that Maxwell quoted agree to within 30 miles a second, both numbers are in error by more than 6000 miles a second. (In another letter, to Sir William Thompson, dated Dec. 10, 1861, Maxwell ascribed a velocity of 195 777 miles per second to Fizeau.)[6] However, in his published paper four years later he gave the values in kilometers per second, which are quite different from the Kohlrausch and Weber units in meters per second and

". . . we have strong reason to conclude that light itself—including radiant heat, and other radiations if any—is an electromagnetic disturbance in the form of waves propagated through their electromagnetic field according to electromagnetic laws."

From those of Fizeau; the velocity of light was not accurately known at that time.

Other investigations

Maxwell investigated the kinetic energy that might possibly be possessed by an electric circuit when in rapid motion, and in 1861 he constructed an apparatus to determine its value. The apparatus consisted of a central electromagnet capable of being rotated about its horizontal axis between pivots, and a ring which revolved about a vertical axis. There was independent neutralization of the earth's field and the pivots were used as conductors to energize the coil. Any possible angular movement of the coil toward the vertical was observed during the rotation of the ring. Maxwell operated the device and concluded that if a magnet contained matter in rapid motion, the angular momentum of such rotation would be very small compared with any measurable quantities. He also constructed a dynamical model to demonstrate the equations of electric currents, as in the case of two inductive circuits. From Faraday, Maxwell derived the notion that a magnetic field was wrapped around a current, and thus, conversely, that a current could be wrapped around a magnetic field. This led him to express the reciprocal relationship in his mathematics with a term he called "curl." As a next step, when the two fields coexisted in space, he expressed the relationship as the curl of a curl, which found its way into his equations for electric waves. He coined the term "div" for divergence or rate of change of the density of the lines of force.

Although best known for the enunciation of the electromagnetic field theory and that of light, he also made fundamental contributions to the growth of thermodynamics and the kinetic theory of gases. Inspired by the work of Clausius, Maxwell analyzed both mathematically and experimentally the heat content of a substance and the rational energy of its molecules. He determined the average number of collisions in a given time and the mean free path of the molecules, which he related to the viscosity of various gases. His keen mathematical analysis of molecular forces and in optics (particularly in color

vision) set Maxwell apart as one of the great minds in the interpretation of physics in the latter half of the 1800s.

In 1871, Maxwell was appointed the first professor for the newly founded chair of experimental physics at Cambridge. Here, he devoted himself to the task of establishing the Cavendish Laboratory, which became a fountainhead of physical knowledge. (Here Ohm's law for metallic conductors was verified.) It was therefore fitting that shortly thereafter Maxwell should dedicate the last five years of his life to editing the papers of the eccentric genius, Henry Cavendish (1731–1810), who in his lifetime had published only two papers, but who had left 20 packages of manuscript notes on chemistry, physics, and experimental electricity. With his usual thoroughness, Maxwell copied all of the papers in his own hand and organized the material by subject matter. He read the books of the early period and repeated the experiments of Cavendish, even to the point of using his own body as a galvanometer to sense current intensity. The *Electrical Researches of the Honourable Henry Cavendish*, which appeared in 1879, showed that concepts such as Ohm's law, specific inductive capacity, and the notion of potential were clearly understood by Cavendish. This was Maxwell's last contribution to science; he died a few weeks after its publication. The appearance of the Cavendish papers was the last of more than a hundred studies that Maxwell published in the short span of his lifetime.

At the Cavendish, the birthplace of nuclear physics, important experiments were made in electromagnetic theory; these established that the unit of charge in electromagnetic units bears a ratio to the unit of charge in electrostatic units, which is numerically and dimensionally equal to the speed of light. Maxwell predicted that light exerts mechanical pressure, which prompted Crookes to devise the radiometer to demonstrate this phase of energy conversion.

Three forms of radiating waves were recognized in Maxwell's time by experimental scientists: the rays of wavelength longer than those in the red end of the spectrum; the rays perceived as visible light; and the shorter wavelengths of the violet end of the spectrum, revealed by their action on silver salts. Maxwell, using acoustical waves in air as a guide, surmised that other types of radiation may also exist, including those manifest in the range of electrical and magnetic action. He expanded his electromagnetic theory to explain the propagation of light in transparent media, in crystals, and in metals. But because of his inability fully to understand the conditions of transfer at the interface between media, he failed to pursue the problem of reflection and refraction of electromagnetic waves.

The existence of electromagnetic waves had been indicated by Maxwell's equations, but it was 15 years before Heinrich Hertz of Karlsruhe demonstrated the existence of such waves in the space about a discharging Leyden jar. Hertz was a favorite pupil of Helmholtz, the first physicist on the Continent to support the theories of Maxwell. Hertz not only was able to reflect the electromagnetic waves of Maxwell in ways similar to the reflection of light waves, but also was able to bring them into focus, to polarize them, and, through a number of brilliant experiments demonstrating interference patterns, to establish the wave character of the radiations and calculate their wavelengths. Later, he expanded the experiments by using induction coils having terminals joined to metallic sheets and spaced balls. A spaced second conductor with a small gap in its circumference showed that oscillatory discharges took place between the metal sheets in the form of sparks that also appeared in the gap of the secondary detector. Hertz calculated the value of the velocity of propagation in air and found it, as Maxwell had predicted, to be the order of that of light. The remarkable demonstration of Hertzian waves stimulated the imagination of many workers in this field of electrical investigation, but others had to carry on his work because Hertz died when only 37 years of age. Marconi, and others, applied Hertzian waves to radio communication and to broadcasting. This constituted one of the most advanced steps in the history of mankind, for the social influence of radio has exceeded even the revolutionary consequences that followed upon the invention of printing in the 1450s.

Although Maxwell's life was short, even by the standards of his own time, he accomplished much of prime importance. In 1860 the Royal Society presented him with the Rumford Medal for his research in light and in the following year he gave his first lecture at the Royal Institution under the sponsorship of Faraday, whom Maxwell admired more than anyone else among his colleagues. Maxwell delivered the inaugural lecture at the Cavendish Laboratory in 1871, but actual research did not commence there for another three years. He sponsored popularization of difficult scientific subjects and contributed his own work, *Matter and Motion*, as an example of a simple and lucid presentation. He wrote both serious and delightfully humorous poetry, often poking fun at his colleagues. He frequently used *dp/dt* (a term in thermodynamics) in place of his signature in friendly communciations. Of his humorous verse, the following two stanzas are half of a "Valentine by a Telegraph Clerk (male) to a Telegraph Clerk (female)":[7]

The tendrils of my soul are twined
With thine, though many a mile apart,
And thine in close-coiled circuits wind
Around the needle of my heart.

Constant as Daniell, strong as Grove,
Ebullient through its depths like Smee,
My heart pours forth its tide of love,
And all its circuits close in thee.

Having no children of his own, he expressed great kindness to young people. In his close and friendly relationship with his students while at King's and at the Cavendish Laboratory, he initiated the custom of inviting undergraduates to work in the laboratories (then considered an unusual practice in Europe) and thereby

"Light consists in transverse undulations in the same medium which is the cause of electric and magnetic phenomena."

to become familiar with the apparatus as well as the discipline of laboratory work. This constituted one of the most important innovations in training in physics and

set a pattern of excellence for which the Cavendish has remained famous.

Maxwell was especially honored, in 1878, by the receipt of a doctorate and the Volta Medal from the University of Pavia, the school where Volta had taught. He was also honored with a doctor's degree from the University of Edinburgh and one from Oxford. He died, after an extended illness, on November 5, 1879, in Cambridge, and was buried at Glenlair. The void left by Maxwell's early death, at the age of 48, is still felt as efforts to understand the physical world more fully move on toward the paths outlined by this consummate interpreter.

The dual property of light as manifested by the correlation between photoelectrons produced by different parts of a coherent beam of light and the excitation of atoms to higher states of energy were observed by thermal vibrations as in a hot metal, or by electron impact as in X-ray discharge. Einstein, early in this century, described a second process of emission in which the atom is induced to release energy while in a state of radiation. Now, a century after Maxwell, Hertzian waves are used to explore an expanding universe through radio astronomy. Such radio waves were first detected by Jansky in 1932, revealing a new concept of the heavens in mass and depth. Thus, the verification by Hertz of the presence of electromagnetic waves in the short-wave region of the radio spectrum was a revelation that opened the way to radio communication, radar, radio astronomy, and the stimulated emission of radiation as currently applied to masers and lasers.

Maxwell's first electrical publication. This is the copy (now at the Burndy Library) he presented to Lewis Campbell, his best friend and biographer.

Lewis Campbell
from his friend
J. C. Maxwell.

ON

FARADAY'S LINES OF FORCE.

FROM THE TRANSACTIONS OF THE CAMBRIDGE PHILOSOPHICAL SOCIETY.
VOL. X. PART I.

BY J. CLERK MAXWELL, B.A.
FELLOW OF TRINITY COLLEGE, CAMBRIDGE.

CAMBRIDGE:
PRINTED AT THE UNIVERSITY PRESS,
BY C. J. CLAY, M.A. PRINTER TO THE UNIVERSITY.
M.DCCC.LVI.

Maxwell wove the properties of electromagnetic radiation into field equations which guided Einstein toward the formulation of the special theory of relativity and then on to the relationship between mass and energy, the most important formulation of this century, if not since Newton. Einstein had carefully studied the work of Maxwell and was led to his own principles by the very method of Maxwell. In his tribute to the immortal Scot during the centenary of his birth in 1931, Einstein wrote:

"If we leave aside the important special results which Maxwell contributed in the course of his life to particular domains of physics, and confine our attention to the modification that he produced in our conception of the nature of Physical Reality, we may say that, before Maxwell, Physical Reality, in so far as it was to represent the process of nature was thought of as consisting in material particles, whose variations consist only in movements governed by partial differential equations. Since Maxwell's time, Physical Reality has been thought of as presented by continuous fields, governed by partial differential equations, and not capable of any mechanical interpretation. This change in the conception of Reality is the most profound and the most fruitful that physics has experienced since the time of Newton."[8]

The influence of Maxwell that led beyond the discoveries of Hertz also prompted Max Planck to write:

"Neither Faraday nor Maxwell may have originally considered optics in connection with their consideration of the fundamental laws of electromagnetism. And yet the whole field of optics, which had defied attack from the side of mechanics for more than a hundred years, was at one stroke conquered by Maxwell's Electrodynamic Theory; so much so that since then every optical phenomenon can be directly treated as an electromagnetic problem. This must remain for all time one of the greatest triumphs of human intellectual endeavour. . . .His name stands magnificently over the portal of classical physics, and we can say this of him: by his birth James Clerk Maxwell belongs to Edinburgh, by his personality he belongs to Cambridge, by his work he belongs to the whole world."[9]

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